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AN ENGINEERING TEST FACILITY FOR HEAVY ION FUSION – OPTIONS AND SCALING

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ABSTRACT

The engineering test facility (ETF) for inertial fusion energy (IFE) is the development step preceding a demonstration power plant. As such, it must demonstrate, in an integrated facility, performance of all the key subsystems required for fusion energy production, including target production, injection and tracking, beam propagation and focusing, target gain and yield, chamber response and recovery between shots, heat removal, tritium recovery, and plant safety. In the present work, we combine our current understanding of the target physics and technology, thick liquid wall chambers, and a heavy ion driver to investigate integrated system scaling and operating scenarios for an ETF for heavy ion fusion.

I. INTRODUCTION

The ETF is a key facility in the development of fusion energy. Our previous work on the ETF step focused on approaches to minimize the development cost, which is still considered an important goal.[1] Since that time, substantial progress has been made on target designs for heavy ion fusion, thick-liquid-wall chamber designs, and accelerator design and technology. For example, integrated 2D target physics calculations have been completed for distributed-radiator target designs, and the performance of these targets (i.e., gain) has been scaled down to driver energies below 2MJ (Ref. 2) Geometric scaling relationships have been developed to allow proper scaling of key fluid mechanic phenomena with target yield and rep-rate.[3] Significant work has also been devoted to developing cost and performance modeling for heavy ion drivers based on compact, multi-beam quadrapole arrays.[4] In the present work, we combine our current understanding of the targets, chamber, and driver to investigate integrated system scaling and possible operating windows for a heavy-ion driven ETF.

Three key, independent ingredients will be required prior to construction of the ETF. First will be the demonstration of indirect-drive ignition and gain on the National Ignition Facility (NIF), to confirm capsule physics models. Second will be experimental results from an integrated research experiment (IRE) confirming the source-to-focus capability of heavy-ion drivers under scaled conditions, and the target physics for heavy-ion x-ray production for indirect drive. Third will be technology development for chambers, targets, and system integration, leading to the engineering capability to design these systems with predictable cost and reliability. Because IRE target results will be required for the design of IFE-specific capsules to be tested on NIF, current planning calls for parallel work in each of these three areas, providing the basis for an ETF construction decision around 2010.

As currently envisioned, the ETF will include both a single-shot test chamber to optimize target designs in a precisely controlled and diagnosed manner (much the same way as current ICF target physics experiments are conducted) and a high repetition rate (rep-rate) chamber to investigate, at reduced chamber size and target yield, all of the important phenomena which govern IFE power plant operation. The ETF will accomplish many things including the following:

1) System Integration: Perhaps the most important function of the ETF is the integration of all the necessary subsystems and technologies needed for an IFE power plant. This includes the driver, driver/chamber interface, targets, fusion chamber, and heat transfer systems.

2) Target Physics: The ETF will be used to optimize heavy-ion driven targets in a single pulse chamber. It will map out an important portion of the gain versus driver energy space by varying the drive energy and target design parameters.

3) Driver Technology: The size of the driver needed for an ETF is an important question from the standpoint of

physics, engineering and economics. The driver must be large enough to reliably ignite targets and produce significant yield per shot and large enough to demonstrate the technologies needed for a power plant driver. Beam propagation and focusing through post-shot chamber environment will be demonstrated at rep-rate in the ETF.

4) Chamber Technology: The ETF will provide the first integrated nuclear tests of the chamber technologies. This is critical for the thick liquid wall chamber design since neutron heating of the fluid can generate locally high liquid velocities.

5) Target Technologies: Target production at higher rep-rate and precision (because of smaller capsules) will be required for the final, average-power testing phase of the ETF. Target injection and tracking will also be required at these higher repetition rates.

6) Nuclear Technology: The ETF will provide integrated tests of neutron damage to first wall, blanket materials, and final focus magnets at accelerated rates (due to less shielding). It will also demonstrate tritium breeding.

7) Heat transfer and other plant systems: The ETF will produce several hundred MW of power that must be removed from the chamber. Conversion to electricity is optional (i.e., it may be sufficient simply to produce the required steam conditions needed to run a turbine). The ETF must also demonstrate tritium recovery from the breeding blanket and recycling to the target production facility.

In this paper we consider how the key design features of these different subsystems scale with characteristics of the ETF. Different scaling parameters are important for different subsystems. Driver energy (i.e., beam energy delivered to the target) is the key scaling parameter for driver technology since it the primary factor determining the driver cost and will likely dominate the cost of the ETF. For target physics, the key input is driver energy and key performance measures are gain and yield. Chamber scaling depends on yield, size, rep-rate, and power. Target fabrication, injection and tracking technologies are best characterized by rep-rate and the scale of the targets, which depends on yield. Neutron heating and damage primarily depend on fusion power and chamber dimensions, but pulse heating is also an important factor. Each of these is considered in more detail in the following sections. A summary of key scaling considerations is given in Table 1.[3]

To provide more concrete discussion, we describe a nominal ETF example, but note that this is not the only possible choice or necessarily optimal. The eventual design will depend on success in the target physics, driver, and chamber development programs leading up to

Table 1. Summary of Key Scaling Considerations.[3]

Geometric scaling
- Key variable is target yield, Y
- Chamber, target injection, and driver/chamber interface dimensions reduced by a factor L
- L scaling with Y chosen to optimally match different key phenomena
- Some dimensions can be adjusted to improve fidelity

Millisecond phenomena
- Liquid/target motion: preserve relative effects of inertia and gravity
    - Liquid/target velocities scale with $L^{0.5}$
    - Repetition rate scales with $(1/L)^{0.5}$
    - Preserves liquid and target trajectories
- Condensation on droplet sprays
    - Droplet number density adjusted to preserve droplet heating (ΔT)

Microsecond phenomena
- X-ray ablation and debris venting
    - Impulse loading effect on liquid trajectory ($L \propto Y^{0.24}$)
    - Ablation layer thermodynamics and hydrodynamics ($L \propto Y^{0.5}$)
    - Pocket energy density / coolant heating ($L \propto Y^{0.33}$)
- Neutron-heating induced liquid motion ($L \propto Y^{0.4}$)

Nanosecond phenomena
- Target output x-ray and neutron spectra/deposition
    - Lower capsule ρr shifts more energy to neutrons
    - X-ray/debris energy partition tuned to adjust ablation mass
- Target/beam physics
    - Most target/beam studies occur in single-shot chamber where initial conditions easily controlled and measured and diagnostics access is easier

Quasi-steady phenomena
- Tritium and heat recovery/chemistry control
    - Use single loop, full height, scale flow area with fusion power
    - Adjust secondary blanket thickness to preserve tritium breeding
- Chamber thermal response
    - Thermal stresses scale linearly with volumetric heating and with L^2
    - Magnet standoff tuned to give acceptable magnet heating
- Chamber damage (activation/corrosion) accelerated

the ETF decision. The parameters for the nominal design are given in Table 2 and compared to the full size power plant design.

Table 2. Nominal ETF Parameters (rep-rate and single shot) Compared to Prototypical Power Plant.

	Example ETF Rep-rate chamber/ Single shot	HYLIFE-II Power Plant
Driver energy, MJ	2.0	3.5 – 6.0
Target yield, MJ	30 / 110	350
Gain [a]	15 / 55	100 – 60
Rep-rate, Hz	9.5 / 0	6.0
Power, MWt	335 / 0	2480
1st wall radius, m	1.2	3.0

[a] depends on target design, higher gains possible

II. TARGET PHYSICS SCALING

We begin with target physics since it likely is the key determinate of the required driver size. Figure 1 shows the predicted target gain as a function of driver energy for one type of HI target design, the distributed radiator target, which has received the most analysis in the last few years.[2] Three curves are shown corresponding to different hohlraum radius to capsule radius ratios (subsequently referred to as HCR for shorthand). The standard HCR is about 2.1 with the hohlraum radius measured at the end of the target. Keeping the capsule size the same and reducing the size of the hohlraum gives the “close-coupled” target design (HCR = 1.6). Since less driver energy is invested in achieving the required drive temperature (~ 250 eV for 400 MJ yield targets), the target gain is higher. This smaller target requires smaller beam spots sizes and is finely tuned to control implosion symmetry. A lower gain curve for a larger HCR of 2.5 is also shown. This should be considered a more conservative design because uniform heating of the capsule is easier to achieve.

The dashed curve in Fig. 1 is an example constant yield curve (Y = 30 MJ in this case) for high rep-rate ETF operation. As indicated, the lower the driver energy the smaller the HCR requirement. Figure 2 illustrates the illumination geometry for the distributed radiator targets. Elliptical beams are focused to illuminate an annular ring on each end of the target. Illumination at the center of the annulus is avoided to prevent waste of energy in heating the beam block that protects the capsule. There is a simple geometric relationship between the size of the beam ellipses required for a given capsule radius and HCR.

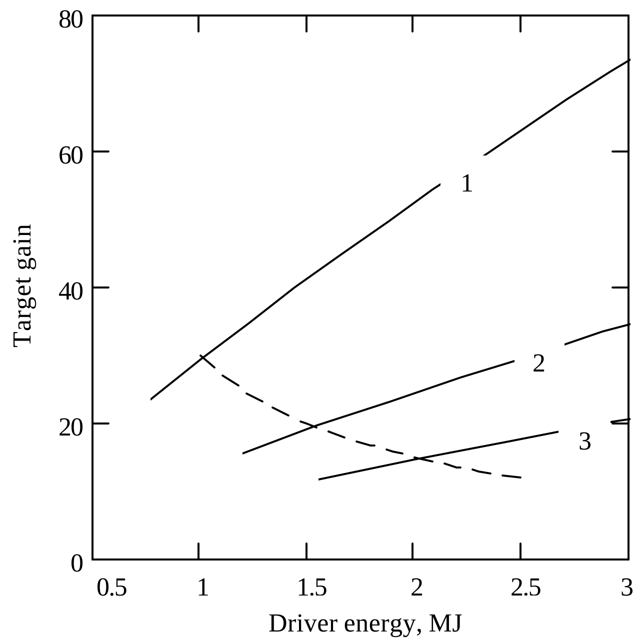

Fig. 1. Target gain (solid lines) versus driver energy for three hohlraum-to-capsule ratios: 1) HCR = 1.6, close-coupled target; HCR = 2.1, standard target; 3) HCR = 2.5, conservative design. The dashed line is the gain for a constant 30 MJ yield. (Note: Gains even higher than curve-1 have been calculated, e.g., by using a lower drive temperature.)

Smaller yield capsule and smaller HCRs lead to more demanding focusing requirements. In this paper we use the effective beam spot size as a measure of beam focusing requirements, which is given by

$$R_{SPOT} = (a^2 + b^2)^{0.5}$$

where a and b are the minor and major axes of the ellipse.

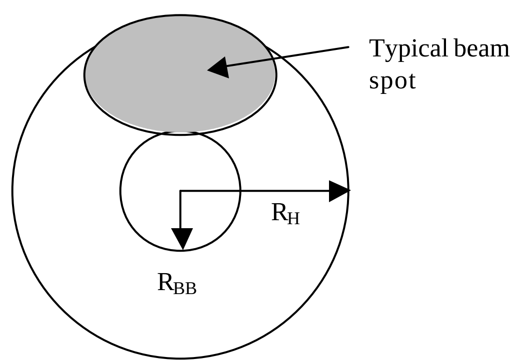

Fig. 2. End view of target showing positioning of elliptical beam (one of many shown). R_H is the hohlraum radius, and R_{BB} is the beam block radius.

For a fixed ETF driver energy, the region of target gain space that can be explored will depend on the ability to control beam spot size and in particular to achieve small spots. Figure 3 adds two lines to the target gain versus drive energy map corresponding to the gain achievable with a fixed spot size. Achieving higher yield at fixed driver energy (moving up) requires smaller spot size (smaller HCR). For example, at Ed = 2MJ, moving from HCR = 2.5 with a yield of 30 MJ to HCR of 1.6 gives gain of 55 and a yield of 110, but the effective spot size must be reduced from 1.4 mm to ~ 1.1mm. A spot size of ~1.2 mm would be adequate for the G = 40 demonstration.

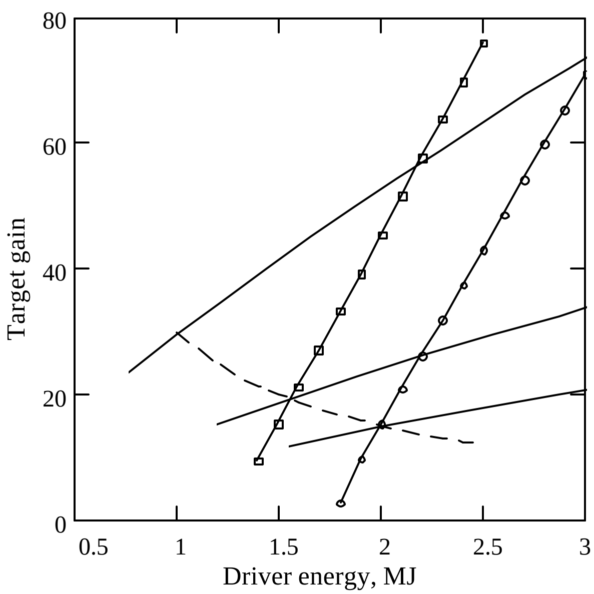

Fig. 3. Target gain versus driver energy with added lines indicating gain achievable for a fixed effective spot size: boxes - spot size = 1.1 mm; circles - spot size = 1.4 mm.

III. DRIVER TECHNOLOGY

A. Spot Size Scaling

Achieving the small spot sizes required by the low yield target proposed for the ETF will be demanding for the driver. The final beam spot size is calculated based on contributions of several effects that prevent point focusing. These include space charge (the tendency of the ions to repel each other due to their charge), transverse emittance (due to velocity components that are not parallel to the beam direction), chromatic aberrations (due to slight variation in the parallel velocity component of ions in a bunch), geometric aberration (which have to do with the finite dimensions of the final focus magnet and size of the beam entering that magnet), and finally the combination of aiming and target positioning errors. Requiring small spot size will require a high degree of neutralization of the beam just prior to entry into the chamber (to minimize space charge effects), careful control of magnetic fields in the quadrapole magnets throughout the length of the accelerator (to minimize transverse emittance), careful control of the accelerating voltages seen by the beam as it passes each accelerator gap (to limit parallel momentum spread and chromatic aberrations). Geometric aberrations are minimized with short magnets and small focusing angles, and aiming errors require accurate injection, tracking and beam pointing. Some of these effects work against each other, e.g., the spot size contribution due to emittance scales at $1/\theta$, where θ is the beam focus half angle of each beam, while chromatic aberrations are proportional to θ. Trade-offs are thus required. For the 2MJ example case, we find that the 1.4 mm spot size can be achieved for the following parameters: 160 beams, singly charged Cs (A = 133), initial pulse duration of 3 μs, final pulse duration of 2.4 ns, 95% neutralized, total final transverse emittance of 1.6 mm-mrad, longitudinal monumental variation $\delta P/P$ of 0.1%, final focus magnet length of 0.5 m, and a beam focus half angle of 0.01 rad (0.57 deg).

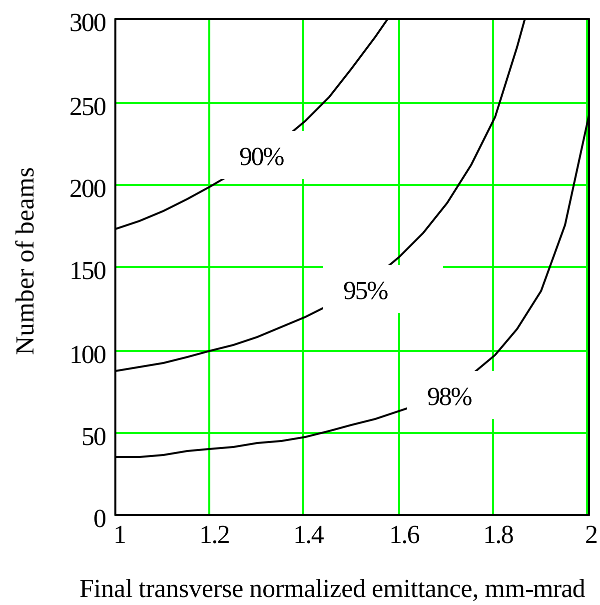

Fig. 4. Number of beams for a 1.4 mm spot size as a function of final transverse normalized emittance shown for neutralization fractions of 90%, 95%, and 98%.

Figure 4 shows the number of beams required to meet the 1.4 mm spot size requirement as a function of the final normalize transverse emittance for three values of neutralization. To preserve the geometric scaling desirable for the chamber dynamics, discussed in the nest section, we would like to have the same number of beams as a driver, which is 160 in recent examples. This would require on the order of 1.6 mm-mrad and 95% neutralization.

B. Driver Cost Scaling

The driver is expected to be the most costly component of the ETF. Heavy ion drivers tend to have a rather high buy-in cost at low driver energy and then scale favorably to higher energies. The reason for this is that a large amount of hardware is required to accelerate ions to the energy required for target heating (typically 1.5–2.0 GeV for Cs and the distributed radiator target). At an average acceleration gradient of 2 MV/m, this requires a 1 km long accelerator. The final beam energy (MJ) produced by the driver then depends on the amount of charge that is accelerated. By building compact quadrapole focusing magnets, a large array of beams (and high total charge) can be transported through common induction cores. Increasing the driver energy by using more beams each carrying the same charge increases the size and cost of the cores, but the net effect is lower cost per MJ of beam energy, at least up to some point. Typically, the total beam energy is delivered by tens to hundreds of beams. Figure 5 shows the normalized cost scaling for an ETF driver. Increasing the driver energy by 50% from the nominal 2MJ to 3MJ only increases the cost by about 28%, while reducing it to 1.0 MJ is estimated to save about 25%.

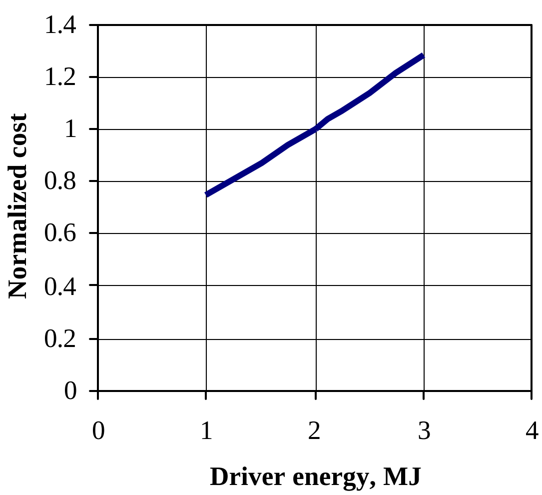

Fig. 5. Normalized driver cost as a function of driver energy relative to 2 MJ design.

IV. CHAMBER SCALING

The primary goal of the high rep-rate operation of the ETF focuses on studying, at reduced chamber size and target yield, all of the important phenomena that govern IFE power plant operation. Because all of the most important phenomena scale somewhat differently with physical size of components and target yield, the design of the scaled ETF systems focuses on minimizing the distortion of the most important phenomena, and providing the ability to vary key parameters like target yield to examine and quantify distortions. Current analysis suggests that distortion levels are quite acceptable with target yields scaled by factors of Y/Yo = 0.03 to 0.15 (i.e., yield of 10–50 MJ should be adequate).

The first and most important ETF scaling choice is the method of geometric scaling of plant subsystems. Our analysis indicates that linear scaling, where all system dimensions (i.e., chamber size, jet diameters, final focus geometry) are scaled by the same factor L (= ratio of ETF to power plant dimensions), will provide the lowest distortions for the chamber, final focus, liquid pumping and condensing systems. Small departures from linear scaling can then be used to tune specific phenomena; for example the final focus magnet standoff distance may be increased somewhat above L to tune the neutron heating effects in the magnets.

The next major ETF scaling choice involves selecting the scaled target injection frequency (i.e., rep-rate). The target injection frequency is scaled to preserve the most important characteristics of the millisecond-time-scale phenomena that occur in the chamber, particularly the clearing phenomena involving liquid hydrodynamics and vapor condensation on droplet sprays. We select the injection frequency so that the relative effects of inertia and gravity are preserved in liquid and target motion, so that the trajectories of droplet sprays and liquid jets, coolant drainage from the chamber and centrifugal pump performance are all preserved. This Froude number scaling requires an injection frequency

$$f \propto L^{-1/2}$$

For the example ETF with L = 0.4, the rep-rate is $(0.4)^{-0.5}$ = 1.58 times the full-scale chamber rep-rate, or 9.5 Hz.

Likewise it also requires that the liquid and target injection velocity scale as

$$U \propto L^{1/2}$$

The next major choice in ETF design is the selection of the scaling between length and target yield Y,

$$L \propto (Y/Yo)^m$$

where m is the power-law scaling parameter.

Figure 6 shows how several key IFE phenomena scale with length and target yield (surface energy fluences, m = 0.5; neutron-induced liquid motion, 0.40; energy density and coolant temperature rise, 0.33; target impulse induced liquid motion, 0.24). Due to their different scaling, not all phenomena can be reproduced simultaneously. By selecting scaling intermediate between the various important phenomena, here m = 0.37 is recommended, the magnitude of distortion of the different phenomena can be made comparable. For an ETF target yield of 30 MJ, compared to 350 MJ for the prototype, this results in a scaling factor of L = 0.40. The chamber, coolant, and shielding masses then scale as L^3 = 0.064, reducing procurement costs substantially compared to full-scale equipment.

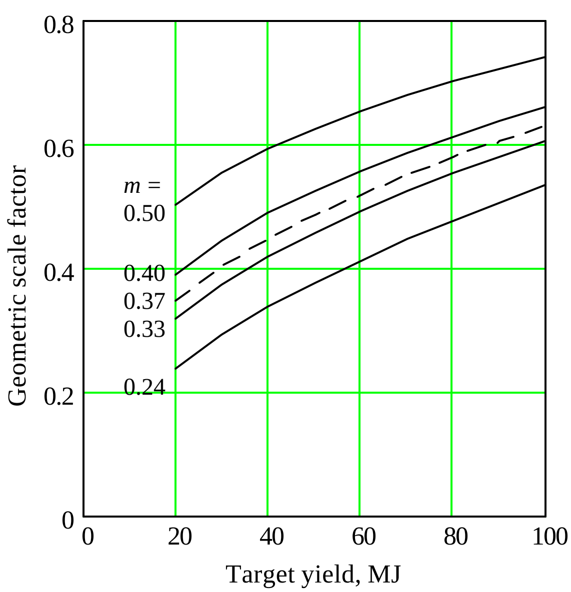

Fig. 6. Chamber scale (normalized dimensions) versus target yield for various scaling exponents in $(Y/Yo)^m$. (Yo = 350 MJ).

The effects of scaling distortion can then be studied in the ETF chamber by operating with a range of target yields. With the conservative energy selection for the ETF driver, higher target yields will be possible, and targets can be tuned to produce lower yields as well. By varying target yields from 10 up to 50 MJ (around the nominal 30 MJ, m = 0.37 value), one can then access energy scaling parameters from m = 0.26 to 0.47.

V. NUCLEAR EFFECTS

The ETF will be the first IFE system with high average fusion power. This will not only provide the opportunity to investigate the pulsed neutron heating induced liquid motion as discussed in the previous section, but also to gain radiation damage data on the first wall, blanket and final focus magnets. Using the reduced scale chamber as suggested in Section IV, reduces the amount of first wall shielding more rapidly than the fusion power, leading to higher neutron flux and more rapid damage accumulation than for the full size chamber. Table 3 compares some key nuclear parameters for the example ETF and a power plant chamber. For the ETF final focusing magnets, we have assumed that no shielding would be used—this results in the smallest possible array angle. Note that the magnetic heating per shot is low enough to avoid quench.

Table 3. Comparison of Key Nuclear Parameters.

	ETF	Power Plant
Yield, MJ	30	350
Rep-rate, Hz	9.5	6.0
Fusion power, MW	285	2100
Thermal power, MWt [a]	335	2480
Capacity factor	50%	80%
1st wall radius, m	1.2	3.0
1st wall annual fast n^o fluence (> 0.1 MeV), n/cm^2-y	1.3×10^{22}	1.6×10^{21}
1st wall heating, W/cm^3	166	37
TBR (pocket/total) [b]	0.55 / 1.23	1.18 / 1.26
Magnets heating in coils, mJ/cc per shot	0.46	0.07
Magnet annual fast n^o fluence (> 0.1 MeV) to coils, n/cm^2-y	1.5×10^{18}	4.1×10^{17}
Magnet annual dose, MGy/y	64	1.5
Estimated magnet lifetime, years of operation	1.6 - 6.7	24 - 66

[a] with blanket multiplication
[b] pocket refers to the flowing blanket of flibe surrounding the target and protecting the first wall

For example, at 0.4 scale with 30 MJ, 9.5 Hz operation, the annual fast neutron fluence (accounting for the difference in capacity factors) at the first wall is ~ 8× higher in the ETF than for a power plant. While magnet heating per shot is still quite low for the ETF (magnet quench is avoided), the total dose to the insulators and the annual fast neutron fluence to the superconducting coils are increased by 43× and 3.7×, respectively. As a result, an ETF final focusing magnet may only last 1.6-6.7 years, while it is a lifetime component for a power plant. The ETF will provide interesting radiation damage data without construction of an expensive materials testing facility. If the magnet lifetime needs to be increased, frontal shielding could be added or the array angle could be expanded to allow for radial shielding

VI. HEAT REMOVAL AND TRITUM RECOVERY

A typical full size power plant will have two to four primary heat transfer loops and steam generators. Although the thermal power of the nominal ETF is only 335 MWt, heat transfer components closer to full size can be demonstrated by using only one loop with the ETF instead of four (e.g., a single 335 MWt loop compared to 620 MWt for a four loop plant shown in Table 2). For the steam generators and tritium disengagers the important boiling and mass-transfer phenomena depend on the elevation in these systems, so for these systems we select full height scaling, reducing the number of loops from four to one and then reducing the cross-sectional area of the remaining loop (e.g. number of steam generator tubes) as necessary to keep flow area proportional to the fusion power.

Producing electricity with the ETF is optional, but in our view desirable. The value of the electricity, which could be used to run the driver, and the value of a first demonstration of fusion electric power is probably worth the investment in a turbine/generator set. Even at the low gain and low yield operating point, the example ETF could produce 134 MWe compared to the driver power requirement of 54 MWe (ηd = 35%). Plant pumping and other power needs would further reduce the amount available for export to the grid, but net power production is clearly possible.

VII. BEYOND ETF

Finally, we note that it may be possible to use the ETF driver for the demonstration power plant (Demo) stage following completion of ETF testing. If higher yield targets can be reliably ignited with the ETF driver (e.g., by using smaller HCRs), larger chamber, heat transfer, and power conversion components could be built and used with the existing driver. Alternatively, the driver might be upgraded by adding more beams to produce the higher gains and yields needed for the Demo. Results on the ETF will define the path to Demo.

VIII. CONCLUSIONS

The ETF is a key development step because it will be the first fully integrated, high rep-rate demonstration of all the key subsystems required for an IFE power plant. From an economic point of view, it is desirable to operate the ETF at small scale (e.g., E ~ 2 MJ, Y ~ 30 MJ) to keep the cost of the driver low, simplify the fabrication, testing and optimization of chamber equipment, and minimize the power handling requirements. To access this most desirable operating space requires several things:

- Target gain > 15 with small capsules (but larger than NIF)
- Beam focusing to small spot size (< 1.4 mm)
- Target production at higher rep-rate (~ 9.5 Hz) and precision than commercial systems

The ETF will provide flexibility in developing heavy ion fusion. It will use beam switching to two (or more) chambers so that both single shot target physics tests (including maximizing yield) and high rep-rate chamber tests can be conducted with the same driver. Also, the ability to vary the target yield by varying the target design (e.g., hohlraum-to-capsule ratio, tritium loading) and/or the driver energy will allow a variety chamber phenomena to be simulated more closely.

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